

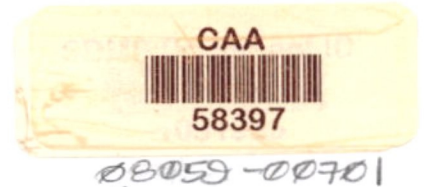


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June 16, 2003

Mr. William A. Keefe, Esq.  
Gorsuch Kirgis LLP  
Tower I, Suite 1000  
1515 Arapahoe Street  
Denver, Colorado 80202

**RE: Engineering Review of Leyden Gas Storage Facility Closure Plan,  
Docket 0304-GA-02, Colorado Oil and Gas Conservation Commission**

Dear Mr. Keefe:

Per your request, we have reviewed the petroleum engineering aspects of the Leyden Gas Storage Facility Closure Plan prepared by Public Service Company of Colorado ("PSCo"). The purpose of this review is to evaluate the adequacy of the Closure Plan to protect public health, safety and welfare and the environment.

For the most part, our analysis focused on the following topics:

- Natural gas storage at the facility
- The potential for gas leakage out of the facility
- The methods to be used to abandon wells
- The amount of gas remaining in the facility at closure
- The proposed use of the facility for water storage.

From our analysis regarding these factors, it is our opinion that the Closure Plan proposed by Public Service Company of Colorado will protect public health, safety and welfare and the environment in the following ways:

1. PSCO will remove as much of the gas as they reasonably can.
2. By filling the system with water, PSCo will displace more of the gas out of the facility than would be recovered solely through depletion.
3. Although there will still be some volume of gas remaining underground, as long as there are no breaks in the Upper/Middle Laramie caprock, there should be no mechanism for gas migration to the surface.
4. The gas remaining underground will be in isolated, small pockets that are unlikely to be penetrated by any possible future drilling in the area.
5. By plugging the wells that are not needed for water storage with cement from surface to total depth, PSCo will be eliminating any chance for gas migration through those wells, and will remove or reduce any temptation for those wells to be reentered by other parties in the future.

If you have any questions regarding this report, please give me a call. Thank you.

Sincerely,

QUESTA ENGINEERING CORPORATION

A handwritten signature in black ink, appearing to read "Dave O. Cox", written over a horizontal line.

By Dave O. Cox, Senior Consultant

DOC:msw

Document Reference No. 03DOC020.DOC

## **NATURAL GAS STORAGE AT THE FACILITY**

The Leyden Facility is located northwest of the city of Denver in a former coal mine at depths from about 700 to 1000 feet below the ground surface. The Leyden Coal Mine operated from 1903 to 1950. About 6 million tons of coal were removed during that time, leaving a void of about 150 million cubic feet. After engineering screening in 1958 and pilot testing in 1959-1960, PSCo brought the Leyden Facility into operation in 1961. A maximum of about 3.0 billion standard cubic feet of natural gas could be stored in the facility at a pressure of 250 psi if there were no water in the mine.

The Leyden Facility is contained in the Lower Laramie Formation. The Laramie Formation contains several lithologies, including (in order of abundance from Camacho): shale, claystone, siltstone, sandstone and coal. The Upper/Middle Laramie is exposed at the surface, or is covered by gravel or alluvium. The Upper /Middle Laramie is primarily made up of shales, claystones and siltstones, while most of the sandstones and coals lie in the Lower Laramie. The sandstone units are generally lenticular in nature, and very few of them are correlatable from well to well. The Leyden mine is located in two coal seams in the Lower Laramie, designated as the "A" and "B" seams. Below the Laramie lies the Fox Hills Formation, which is a fine-grained sandstone that is the main aquifer in the area. Several thousand feet of Pierre Shale underlies the Fox Hills. Structurally, this area is located on the western margin of the Denver Basin, with bed dips of a few degrees in the mined area.

To understand the mechanics of gas storage in the facility, it is necessary to first understand what happened at the mine and subsequent to mining. A conceptual cross-sectional view generally from northwest to southeast across the area will be used to facilitate understanding of the gas storage facility. The conceptual section starts just northwest of Leyden Well #32, then passes southeasterly to Leyden Wells #32, #34, and #31 (**Figure 1**). From Well #31, the line of section turns to the west-southwest to Leyden Well #17, then to an in-mine hole (Mine Hole #19). From Mine Hole #19, the section turns southeast again, to pass through Shaft #4 and Leyden #36. **Figure 2** shows a conceptual cross-section through the area prior to mining. Key features to be noted on this conceptual section are the thickness of several hundred feet of Upper/Middle Laramie throughout the area, forming a seal over the facility, the presence of the two mined coal seams (among several) in the Lower Laramie,

and the presence of two (among numerous) sandstone bodies in the Lower Laramie. The "B" Seam is not present in Well #36. It is also to be noted that there is a slight dip in a generally southerly direction.

By the time mining had been completed (see **Figure 3**), a considerable volume of coal had been mined from the No. 1 and No. 2 mines on the east in the "A" coal seam, and the No. 3 mine on the west in the "B" coal seam. Mining in the "A" seam occurred from 1903 to 1917, while the "B" seam was mined from 1913 to 1950. So far as is known, the only connection in the mines between the two seams was through an air shaft designated as Shaft #4. The mines were room and pillar mines. In addition to the shafts, drifts and rooms in the mine, there were also a number of drillholes drilled from the surface to various depths to explore for coal, and several mine holes drilled vertically upward in the roof of the mine or down in the floor of the mine to search for more coal. The locations of the mine holes are drillholes are known from maps prepared during the mining era. Two holes associated with mining are on the conceptual cross-section shown on **Figure 3**: Drillhole #4 drilled from the surface, and Mine Hole #19 drilled up and down from the mine. Drillhole #4 was outside the area with underground mine workings.

**Figure 4** shows a conceptual section across the area at the time the gas storage facility was installed. When mines are abandoned, there are commonly rock falls from the roof that fill up the mined void. In shallow mines, this can lead to subsidence, but in deeper mines such as Leyden, the rock falls reach a stable point where the rock or rubble piles that have formed then support the overlying rocks. The gas storage wells drilled at Leyden generally encountered competent (unbroken) rock until they reached a level about 60 ft, more or less, above the mined seam.

By the time the first storage wells were drilled, the mine workings had filled up with water. This occurred because the Lower Laramie formation is part of the Lower Laramie – Fox Hills aquifer, which is a regional aquifer. There were some isolated pockets of air and coalmine methane trapped by the advancing water.

A pilot test was conducted in 1959-1960 to confirm the suitability of Leyden for gas storage. It was recognized at that time that the injected gas would physically be stored in the cavern, the broken rock filling and above the mined out zones, and also in minor amounts in sandstone beds that might be in hydraulic communication with the cavern.

PSCo has now operated the Leyden Gas Storage Facility for more than 40 years since its original approval by the Colorado Oil and Gas Conservation Commission. **Figure 5** shows the conceptual cross-section with additional wells that have been drilled since the inception of storage operations. In 2000 PSCo decided to close the facility.

### **THE POTENTIAL FOR GAS LEAKAGE OUT OF THE FACILITY**

In order to evaluate the potential for gas leakage from the facility, historical occurrences of gas leakage were reviewed. During the last 40+ years, there have been six significant occurrences of identified gas migration or movement outside the immediate area of the mine workings. In every instance, the gas movement occurred as a result of mining or gas storage activities. Other instances of leakage from wells above the mine workings were remediated by PSCo.

The following several paragraphs review the circumstances of the incidents of gas movement out of the immediate area of the mine workings:

- **Well #17.** In 1964, gas was observed bubbling up through ice in Barbara Gulch where Well #17 is now located. Although this location is outside the area of mine workings, the old mine maps indicate a drill hole (Drill Hole #4) was drilled from the surface through the coal seams at this location. An unplugged hole was found at this site, and was reentered, cased and completed as Well #17. It would not be expected that a well this far from the workings should have gas in it, but a plausible mechanism for gas migration can be seen from **Figure 4**. A vertical hole (Mine Hole #19) was drilled 118 ft upward from the mine at a location southwest of Well #17. The driller's log on the coal mine map indicates this hole penetrated to within a few feet of the equivalent stratigraphic location of a porous sand body found in Well #17 (the so-called "Z-2 Sand"). There would have been no way for the miners to effectively plug a vertical hole upward from the mine. The mine hole therefore provided a conduit for upward gas migration after injected gas reached its location. With a second opening available through Drill Hole #4 drilled from the surface, the injected gas could pass from the storage cavern, through Mine Hole #19, to the Z-2 Sand, then through that sand to Drill

Hole #4, and up to the surface. Additional evidence exists that indicates this indeed was the case, and will be reviewed in the discussion of Well #31 below. Since the cleanout and installation of casing as Well #17, there has been no further problem with gas migration to the surface at Barbara Gulch.

- **Shaft #2.** In the mid-1970's, bubbling gas was observed inside the liner of Shaft #2. PSCo discontinued pumping from Leyden Wells #7 and #13 to allow the standing water level to cover the bottom of Shaft #2, which eliminated this problem.
- **Well #23.** In 1979, gas was observed leaking out of another old mine drillhole. PSCo cleaned out the hole and cemented casing in place as Well #23, and there have been no further problems reported in this area.
- **Well #27.** This observation well was drilled in 1990 to evaluate a shallow gas zone found in Wells #25 and #26. The gas apparently got into the sand through casing leaks in Wells #15 and #16. Those wells were repaired, and the shallow gas zone at 137 ft depth in Well #27 has shown no significant pressure change since that time, which indicates the gas zone is not in communication with the cavern and has not migrated since Wells #15 and #16 were repaired.
- **Well #31.** In 1993, a small gas pocket was discovered outside the perimeter of the mine cavern in Well #31 in a Lower Laramie sandstone unit designated as the "Z-2 Sand" at log depths from 663 to 669 feet. The Z-2 Sandstone was only found in two out of the 39 wells and test holes drilled in or around the facility. The presence of gas was evident on both the neutron-density log and the mud log in Well #31. Following completion as a monitor well in the Z-2 Sand, at various times the well would contain either water or gas, indicating the gas pocket at Well #31 has limited areal extent. If there were more gas present in the zone, the water level would not periodically rise above the zone. Furthermore, the gas in Well #31 contains helium in amounts consistent with gas injected into the facility

in the 1960s and 1970s, while gas injected more recently contains much less helium. Accordingly, the gas in Well #31 is "old" storage gas from many years ago. The presence of "old" gas in a small pocket in the Z-2 Sand at Well #31 is consistent with the explanation provided for the leakage observed at Well #17. While Drillhole #4 was open, the water in that sand could drain and be replaced by storage gas. After the drillhole was cased and cemented as Well #17, the water level in the Z-2 Sand equilibrated sufficiently with the pressure in the mine that the gas formed isolated pockets such as that found in Well #31.

- **Well #36.** After gas was found in Well #31, PSCo drilled eight additional holes (Wells #32-36 and Test Holes #1-3) to search for other possible indications of movement of storage gas from the original facility area. The only one of those eight holes which had any significant volume of gas was Well #36, where storage gas was found in 1999 gas in a Lower Laramie sandstone about 775 ft below ground level outside the perimeter of the mine cavern. In contrast to the indirect connection observed in Well #31, testing of Well #36 indicated the same composition as recent storage gas, and high pressures and rates consistent with a relatively direct connection to the main facility area. Inasmuch as the gas sand is located only about 100 feet above the "A" Seam, it is likely that sand itself forms the connection between Well #36 and the broken rock in the collapsed region above the mine. The permeability computed from a test of Well #36 was 625 md, so this sandstone unit happens to have much greater permeability than most Lower Laramie sands, which have a median core permeability of 0.3 md.

The above instances are the only cases of significant gas movement out of the cavern or collapsed volume above the cavern.

There were several minor gas shows on mud logs or neutron-density logs of the wells outside the mined area, but these are not considered significant. They included:

- **Well #33** had gas shows on the mud log above 100 feet depth, and a coalbed methane show around 500-530 feet depth.

- **Well #35** had small neutron-density log crossovers from 797- 805, 928-930, and 944-945 ft that are statistical effects caused by higher than normal variability in the log measurements ( $\pm 1\%$  for density log,  $\pm 2.5\%$  for neutron). A very small (1 unit) mud log gas show at 778 ft, if real, was a small coalbed methane show from grinding up a coal at that depth.
- **Test Hole #2** had mud log gas shows in several intervals from 85 to 348 feet depth which did not have sufficient volume to sample for analysis.
- **Test Hole #3** had coalbed methane mud log gas shows in coal beds.

The above shows were either unrelated to storage gas or were so minor that they did not warrant further investigation.

There have been no indications of significant migration into the Fox Hills or deeper sediments below the Lower Laramie. There is the potential for connection to the Fox Hills through floor heave or through holes drilled down from the mine looking for additional coal. However, this connection is very small, as demonstrated by low rate of water influx into the facility. Well #12, the primary water pumping well for the facility, normally produces about 35 gpm (1,200 bwpd). The Fox Hills is the main aquifer in this area. If there were a significant connection to the Fox Hills, there would be much more water influx into the facility.

There have been no incidents of storage gas above the Lower Laramie except where wells have penetrated the Upper/Middle Laramie. The Upper/Middle Laramie is primarily shale and claystone, totaling several hundred feet in thickness. These units are basically impermeable, and form an effective seal over the facility.

Any potential for gas leakage after closure will be greatly reduced by three factors:

1. The existing wells will be plugged, except those needed for operating or monitoring the facility as a water storage reservoir.
2. Most of the gas will be removed, first by depletion and then by displacement by water injection.
3. Any remaining gas will be left as isolated pockets at depth, below the Upper/Middle Laramie seal. These pockets will occur over a much smaller area than the area that currently contains storage gas.

The impact of these factors is presented in the next several sections of this report.

### **THE METHODS TO BE USED TO ABANDON WELLS**

The Closure Plan presents detailed plans for the abandonment or disposition of each well in the facility. In general, the abandonment procedure involves waiting until the water level reaches above the production casing shoe, and setting a permanent plug at or near the shoe. The well will then be filled with water, and cement bond logs and gas detection logs will be run. If any problems are identified, remedial action will be taken in accordance with Commission rules such as Rule 319 for well abandonment requirements and procedures.

PSCo has indicated that they intend to plug wells with cement from top to bottom. In oil and gas abandonment operations, it is customary to install a series of cement plugs, with the intervals between the plugs commonly being filled with drilling mud or water. The use of cement plugs makes future reentry of an abandoned well much easier. In this case, the existing wells are in or near a zone that is contemplated for potable water storage. Even if water storage were not contemplated, the Lower Laramie / Fox Hills is a recognized fresh-water aquifer. PSCo's plan to fill the casing in abandoned wells with cement from top to bottom should provide maximum protection for the aquifer, while reducing or removing any temptation for oil or gas operators to reenter the well for possible deepening to other zones.

The Closure Plan indicates several of the wells will be used for the water storage facility. Those wells will therefore not be abandoned as part of the Gas Storage Facility Closure Plan.

### **THE AMOUNT OF GAS REMAINING IN THE FACILITY AT CLOSURE**

The amount of gas that will be left in the facility at closure can only be approximately estimated. The same methods that are used to estimate hydrocarbon reserves in natural gas wells can be applied here, but there are certain limitations in the techniques because of the unique aspects of this system. Common methods for conventional reserves estimates include volumetric estimates, material balance and decline curves. Each of these methodologies is considered below.

Volumetric considerations can be used to prepare an estimate of the amount of gas that would remain at closure. Locations of potential gas at closure include:

- **Free gas in the broken rock piles that fill the cavern and the void created by roof falls.** Because of the dip of beds and irregularities in the degree of roof falls, there will still be some gas in the "attic" above the highest withdrawal point in the facility when the facility is filled with water. The maximum "attic gas" volume can be estimated by computing the maximum amount of volume above the highest withdrawal point. Well #9 is the structurally highest well on the west side of the facility, with a casing shoe 5149 ft above sea level. Well #5 is the highest well on the east side of the facility, with a casing shoe 5144 ft above sea level. The trapped gas will be in the rubble pile above the highest withdrawal point. The rubble pile extends approximately 60 feet up from the mined interval. The average extent of the mines is approximately one mile down dip and less than one-eighth mile up dip from the highest withdrawal points in each mine. From geometric considerations using an average dip of  $2^\circ$ , less than 10% of the facility volume will be in the attic when the facility is filled with water (see **Figure 6**). The attic gas will form a roughly triangular cross section, leading to a maximum attic gas volume at 20 psia of about 0.020 Bcf ( $0.020 \text{ Bcf} = 0.10 \times 150 \times 10^6 \text{ ft}^3 \times (20/15.025) \text{ P correction}$ ). The value of 20 psia was selected as a minimum producing pressure that can readily be achieved in the field. (Lower pressures below atmospheric could actually be obtained by using blowers, but this is not recommended. If the facility pressure is reduced below atmospheric, there is potential for air influx occurring.)
- **Trapped gas in inaccessible areas of the facility in and above the mine cavern.** Inasmuch as the gas will be trapped by a slowly advancing water front with low operating pressure, the trapped free gas volume should be small. If it is as much as 5% of the facility volume, and the gas is trapped with an average of 100 ft of water head, the trapped gas volume would be  $0.032 \text{ Bcf}$  ( $0.05 \times 150 \times 10^6 \text{ ft}^3 \times ((20 + 100 \times 0.433)/15.025) \text{ P correction}$ ).

- **Gas trapped in sandstone lenses such as the Z-2 Sand or the gas encountered in Well #36.** The amount of gas recovered to closure from sandstone lenses will depend on the degree of connection between those lenses and the main part of the facility. It is difficult to estimate how much gas may be trapped in such zones. Zones with significant or relatively direct connection to the facility, such as that encountered in Well #36, should become depleted during the withdrawal period prior to closure. Isolated gas pockets such as those in Well #31 would not necessarily become reconnected to the cavern. If a typical Lower Laramie sand body is 10 ft thick, 300 ft wide and 1000 ft long, with 15% porosity, even if it were completely filled with gas, it would only be able to store about 5.5 MMscf of gas at the average operating pressure of the repository of 185 psia ( $10 \times 300 \times 1000 \times 0.15 \times 185 / 15.025 / 10^6$ ). If as many as 10 of these sand bodies were somehow connected enough to the facility to become charged with gas, but were unable to be depleted when the facility is depleted, this would still only account for about 0.055 Bcf.
- **Trapped gas adsorbed in the coal.** Part of the gas injected into the facility has adsorbed on the internal surface of the coal. Leyden was a room and pillar mine, with an estimated 60% of the coal being left behind in the pillars. In addition, there are other coal seams that became part of the rubble pile after roof collapse that would also be able to adsorb part of the gas. There are no measured isotherms for Leyden coal that we are aware of. However, based on the coal type (subbituminous, with a heating value of approximately 9,700 Btu/lb), the gas storage capacity of Leyden coal should be similar to that of typical Powder River Basin coals. The coal remaining in the facility assuming 40% of the volume was mined would be 9 million tons, more or less. Using an average Powder River Basin isotherm from Crockett and Meyer, the adsorption capacity of the coal is estimated to be about 5 scf/ton at 20 psia. This would correspond to an adsorbed volume of 0.045 Bcf ( $5 \text{ scf/ton} \times 9 \text{ million tons remaining}$ ). Even if this value were to be doubled to account for additional coal in the rubble pile and some

adsorption behind the advancing water front, the total adsorbed gas at closure would be about 0.090 Bcf.

In summary, then, the total volumetric capacity of the facility at closure is estimated to be approximately 0.197 Bcf (0.020 Bcf attic gas, plus 0.032 Bcf inaccessible trapped gas pockets, plus 0.055 Bcf possibly trapped in sandstone lenses, plus 0.090 Bcf adsorbed gas). It is important to note that almost half of the estimated gas remaining at closure would be in an adsorbed state and would not be mobile.

The volumetric method can also provide a check against other methods for computing remaining gas at closure by estimating remaining gas in place as of May 1, 2003. About one-third of the facility was filled with water at that time, with a cavern pressure of about 63 psia. Under these conditions, the estimated remaining gas as of May 1, 2003 is:

- **Free gas in the broken rock piles that fill the cavern and the void created by roof falls** of about 0.419 Bcf ( $0.419 \text{ Bcf} = \frac{2}{3} \times 150 \times 10^6 \text{ ft}^3 \times (63/15.025) \text{ P correction}$ ).
- **Trapped gas in inaccessible areas of the facility in and above the mine cavern** will be small because only a part of the facility is currently filled with water.
- **Gas trapped in sandstone lenses such as the Z-2 Sand or the gas encountered in Well #36.** This component would be unchanged from the previous estimate of about 0.055 Bcf.
- **Trapped gas adsorbed in the coal.** At 63 psia, the estimated adsorbed gas content would be about 11 scf/ton, leading to a total adsorbed gas volume of about 0.198 Bcf. However, much of this gas was adsorbed at 150 psia or more, and may not have yet reached equilibrium. At 150 psia, the potential adsorbed gas content would be 22 scf/ton, leading to a potential adsorbed volume of 0.396 Bcf.

Based on the above concepts, a range of volumetric estimates of gas in place as of May 1, 2003 in the facility is from 0.672 to 0.870 Bcf.

Material balance methods are commonly used for moderate to high permeability dry gas reservoirs. In this case, the material balance is complicated by limited water influx from the aquifer, coal sorption phenomena, and the presence of a wide range of permeability settings. Even so, a simple material balance graph (**Figure 7**) was prepared using the cavern pressure and withdrawal data since Oct. 1, 2001, after cessation of gas injection. At these low pressures, the Z-factor correction (non-ideal gas law correction) has limited effect, so the production data are plotted against pressure. Two lines have been drawn through the data. The first line, for the data from 2/1/02 through 8/1/02, indicates a gas in place contributing flow during that period of 1.01 Bcf, which corresponds to 0.35 Bcf remaining as of 8/1/02. This compares well to the volumetric estimate of free gas in the facility of 0.419 Bcf. From August to December 2002, the pressure held relatively steady as more gas was produced, suggesting another source of gas was maintaining the pressure. This may be the result of gas desorbing from the coal, or of gas-charged sandstones or isolated gas pockets now contributing. Since Dec. 2002, pressure again appears to be declining as gas continues to be produced. There are not yet sufficient material balance data to draw a definitive line through these later data points. However, the adjusted remaining balance for the facility prepared by Bill Uding of PSCo, which corresponds to the second line drawn on **Figure 7**, appears to fit the observed data since Dec. 2002 reasonably well.

Production decline curve analysis for the entire facility cannot be reliably performed, because the facility is being produced intermittently. However, decline curve analysis is useful for determining the size of the gas pocket associated with Well #31, which has been vented since late 1999. **Figure 8** shows the rate behavior of this well, and it is clear that the gas rate is declining. A total of about 70 Mcf have been vented from this well. The most recent data show a rate less than 15% of the peak rate. If an exponential decline is applied, this implies about 85% of the ultimately recoverable gas has been recovered. In any case, it is clear that very little additional gas remains to be vented from this well, although there still may be a small amount of unrecoverable "attic" gas in the Z-2 Sand updip of the perforations in Well #31 if water covers the perforations, as it sometimes does.

Although production decline curves are of little use for the facility as a whole, there are several important inferences that can be made from pressure decline (or incline) curves. **Figure 9** presents the pressure response of 8 wells. The lowest curve is the cavern pressure as measured in Well #9 or Well #16. The cavern pressure rose during injection periods, and has generally been declining since injection ceased in Sep. 2001. The pressure in Well #36 has risen and fallen in a fashion similar to the cavern pressure, but with a time lag reflecting some flow restriction in the sand between the collapsed zone above the mine and the well. Well #33, which is completed in the Fox Hills, has shown no apparent impact from variations in mine pressure over time. (The numerous slight drops and recoveries in pressure at Well #33 occur when the pump in the well is turned on.) Wells #10 and #11 are Upper/Middle Laramie monitor wells located above the east and west caverns, respectively. The pressures in these wells actually show slight increases over time, with no apparent impact from variations in mine pressures over time. The observed pressures in these two wells confirm the suitability of the Upper/Middle Laramie Formation as a seal. The pressure in the Fox Hills in Well #31 has declined slightly over the past several years, which is an indication of pressure communication between the cavern and the Fox Hills, but not necessarily flow connection. The reduced pressure on the floor of the mine caused by withdrawals since Sep. 2001 was communicated through the intervening rocks to the Fox Hills, and actually led to a reduction in Fox Hills aquifer pressure under the mine. This change in aquifer stress causes a reduction in pressure under the mine area, which in turn causes water in the Fox Hills to flow from the adjoining areas towards the area under the mine. The same phenomenon caused the pressure to drop in the Fox Hills in Wells #32 and #34. The amount of pressure communication and flow depends on the mechanical properties of the Fox Hills and the intervening strata, as well as the permeability and storage coefficients of the Fox Hills.

### **THE PROPOSED USE OF THE FACILITY FOR WATER STORAGE**

It is proposed to use the Leyden Facility for water storage after the cessation of natural gas storage activities. This concept has several obvious advantages:

- It will provide water to fill up the facility much more rapidly than would natural water influx.

- Water injection will displace a significant volume of gas from the facility, thereby reducing the potential for any gas migration in the future.
- It is economically efficient in that it will allow some of the existing wells to be beneficially utilized, instead of being plugged and abandoned.

These factors are all very favorable. There are, however, some potential hazards from a petroleum engineering standpoint that should be addressed:

1. The first potential hazard relates to possible future drilling. There will unavoidably be some remaining natural gas left in the facility at closure. If the City of Arvada or any other parties drill any new water wells in the vicinity of the facility, blowout prevention equipment should be used so that the drilling contractor can be prepared in case any unexpected pockets of gas are encountered. Well #31 is the well furthest from the mined area that had storage gas in it, at a distance of about 1,000 ft laterally from the mined area. To provide a margin of safety, it is recommended that any wells drilled into the Lower Laramie either above the mine workings, or within one-half mile laterally from those workings, should have blowout prevention equipment.
2. The second potential hazard deals with the contemplated future operation of the facility for water storage. Even after the facility is filled with water, there will be trapped pockets of gas and attic gas present. When water is added to or removed from the facility, part of this gas may be produced. For this reason, the surface and subsurface equipment for the water storage facility should be designed to handle and safely remove any gas production that may occur, and the operators should be trained to handle this potentiality.
3. A third potential hazard relates to maintaining the facility seal. Water storage operating pressures should be kept at a pressure below the fracturing pressure of the caprock at all times.

## **DATA AND DOCUMENTS REVIEWED**

Public Service Company of Colorado, Closure Plan for the Leyden Underground Natural Gas Storage Facility, submitted by Public Service Company of Colorado to the Colorado Oil and Gas Conservation Commission, March 3, 2003.

Public Service Company of Colorado well files for Wells #1 through #36, Test Holes #1, #2 and #3, the Tosco water well and the Church 22-1 gas well, including well file documents, mud logs, geophysical logs and core analyses.

Map of the Leyden Mine.

Public Service Company of Colorado list of Leyden Area Formation Tops.

Previous Leyden Reports and testimony by Dave Cox, Chuck Barrows and Tom Hesemann.

Well test information for the tests performed on Well #31 and #36.

Colorado Oil and Gas Conservation Commission Rules and Regulations, as shown on their web site <http://oil-gas.state.co.us/>.

Testimony, exhibits and findings from the Colorado Oil and Gas Conservation Commission hearing on Cause No. 146, Sep. 30, 1960.

Expert reports from Colorado Oil and Gas Conservation Commission Cause No. 146, Docket No. 9809-SP-07.

Ball, D., "The Leyden Gas Storage Mine", a report prepared for Public Service Company of Colorado, July 29, 1960.

Camacho, R., "Stratigraphy of the Upper Pierre Shale, Fox Hills Sandstone and Lower Laramie Formation (Upper Cretaceous), Leyden Gulch Area, Jefferson County, Colorado", Colorado School of Mines Master of Science Thesis, April 30, 1969.

Colorado Geological Survey, Open-File Report 01-17, *Coalbed Methane Potential In The Upper Cretaceous To Early Tertiary Laramie And Denver Formations, Denver Basin, Colorado*, 2001.

Crockett, F. and Meyer, J., "Update and Revision of Interim Drainage Report on Coalbed Methane Development and Drainage of Federal Land in the South Gillette Area, Campbell and Converse Counties, Wyoming, T. 40-50 N., R 70-75 W.", Feb. 12, 2001, U.S. Bureau of Land Management.

Mallory, W.W., Burnett, P.G. and Warren, S.P., "Geologic and Engineering Aspects of Gas Storage in the Leyden Lignite Mine," Ball Associates (Oct. 1958).

Meddles, R.M., "Underground Gas Storage in the Leyden Lignite Mine", RMAG, 1978.

Raven Ridge Resources, Inc. and Penn, Stuart and Eskridge, "Gas Storage at the Abandoned Leyden Coal Mine near Denver, Colorado", draft report prepared for the U.S. Environmental Protection Agency, Nov. 25, 1988.

Raven Ridge Resources, Inc. and Penn, Stuart and Eskridge, "Legal Issues Related to Coalbed Methane Storage in Abandoned Coal Mines in Colorado", draft report prepared for the U.S. Environmental Protection Agency, June 20, 1988.

Soister, P.E., "Stratigraphy of Uppermost Cretaceous and Lower Tertiary Rocks of the Denver Basin", RMAG, 1978.

Soister, P.E., "Geologic Setting of Coal in Denver Basin", RMAG, 1978.

Wilkinson, L. and Ball, D., "The Leyden Gas Storage Mine, Jefferson County, Colorado", July, 1979.

**Figure 1: Location of Conceptual Cross Section**

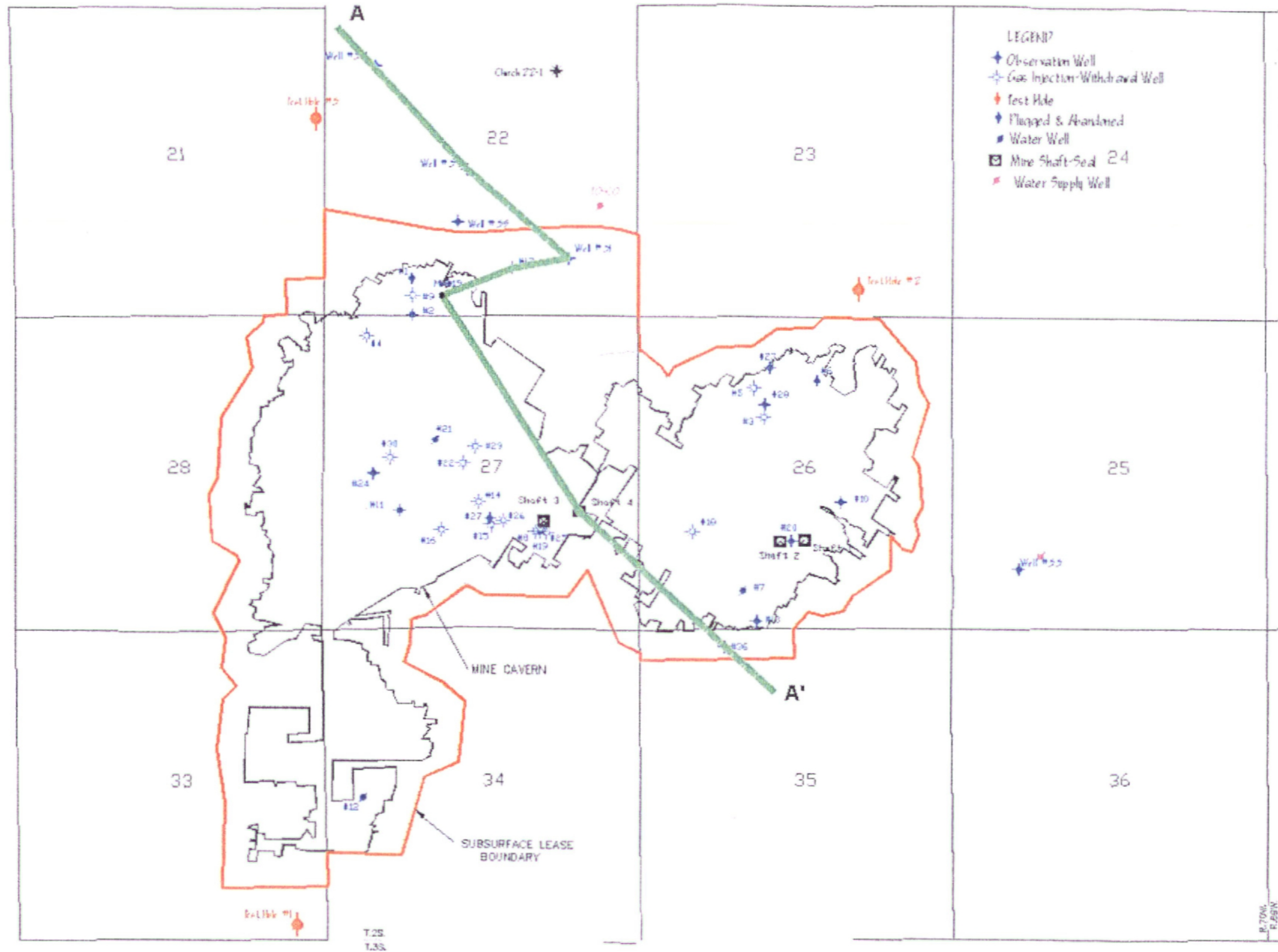


Figure 2: Conditions Before the Beginning of Mining (circa 1900)

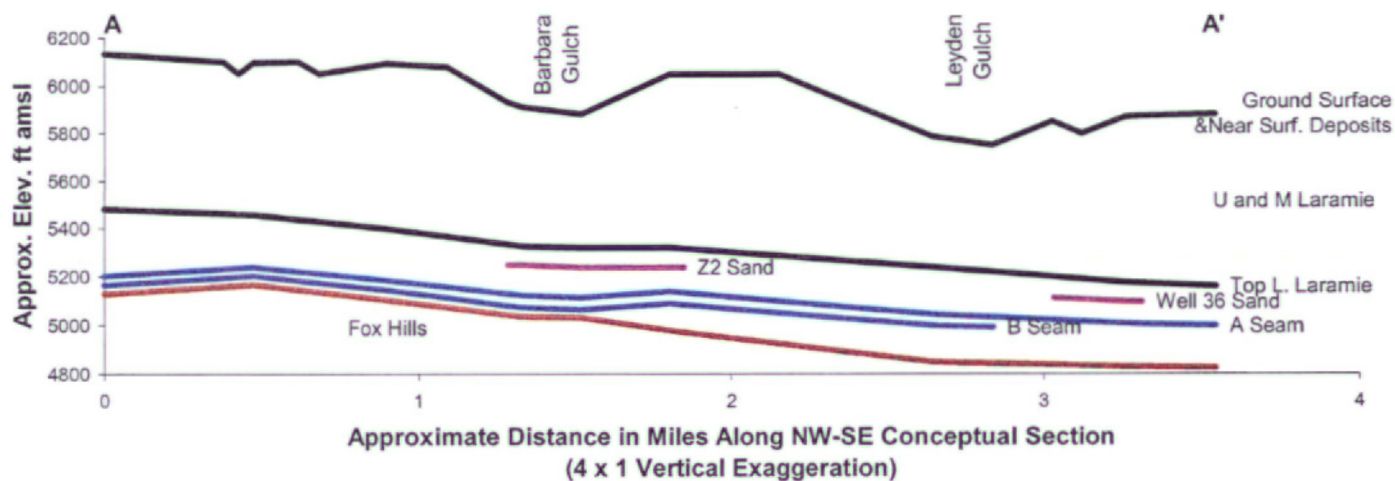


Figure 3: Conditions Near the End of Mining (circa 1950)

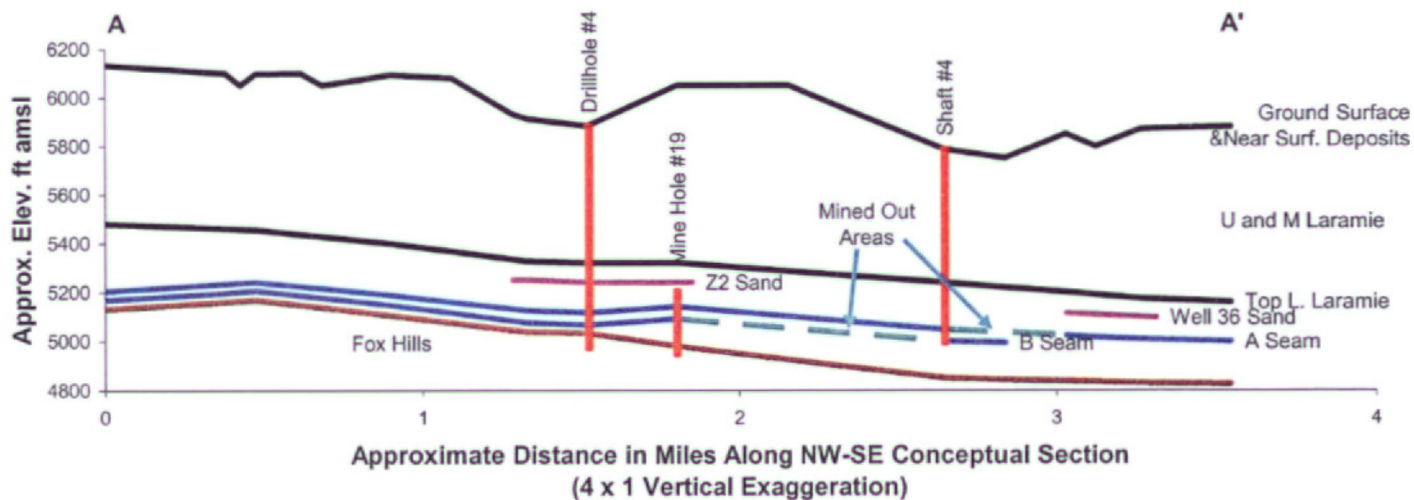


Figure 4: Conditions At Start of Storage (circa 1960)

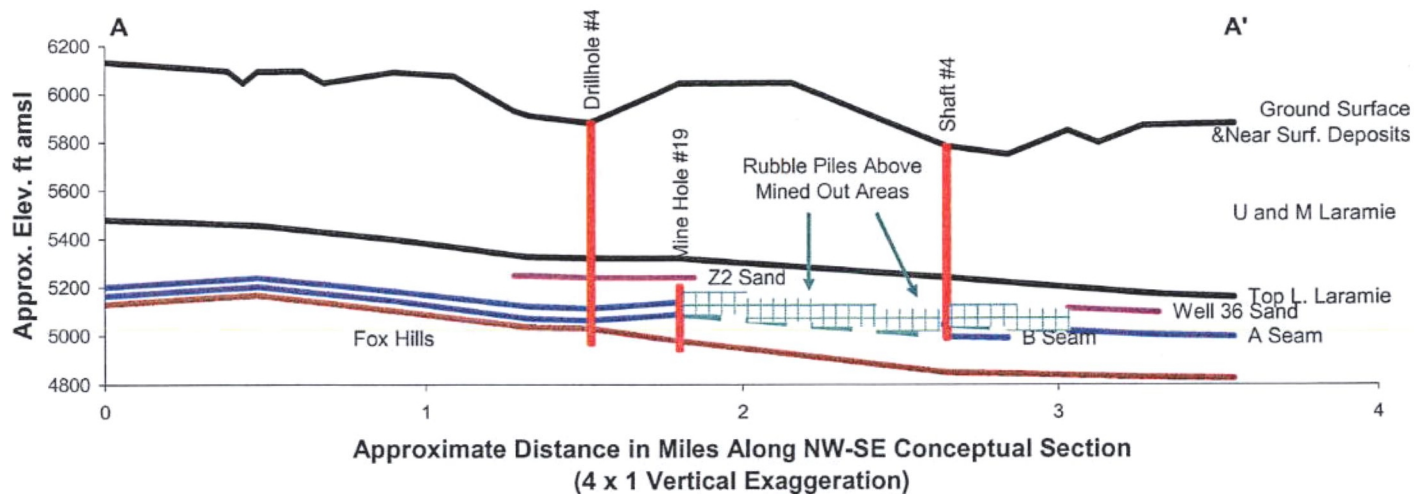
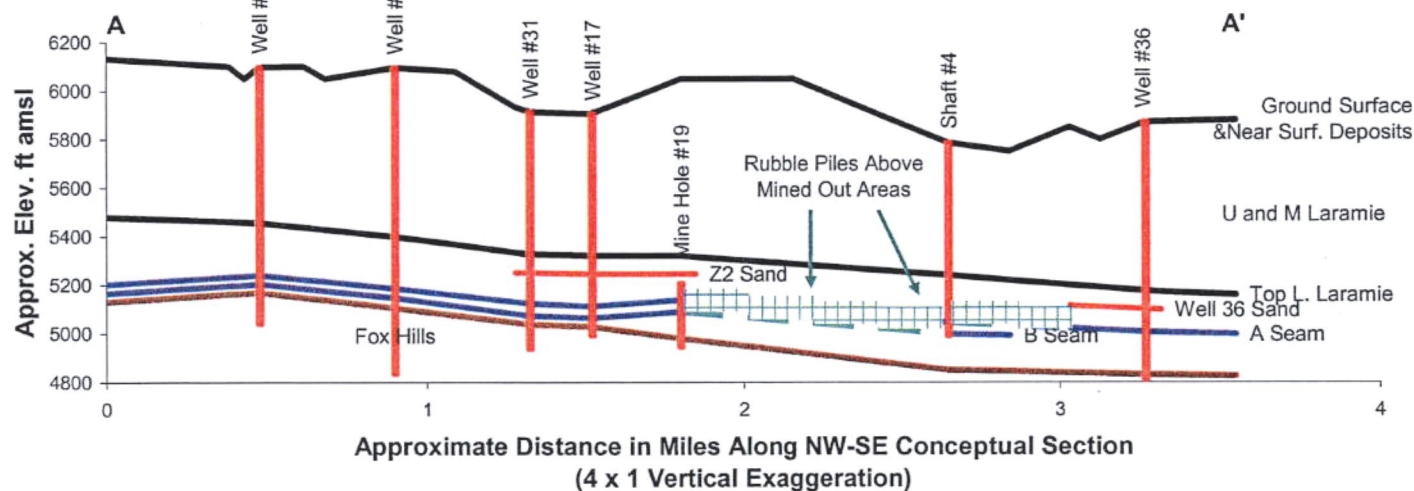
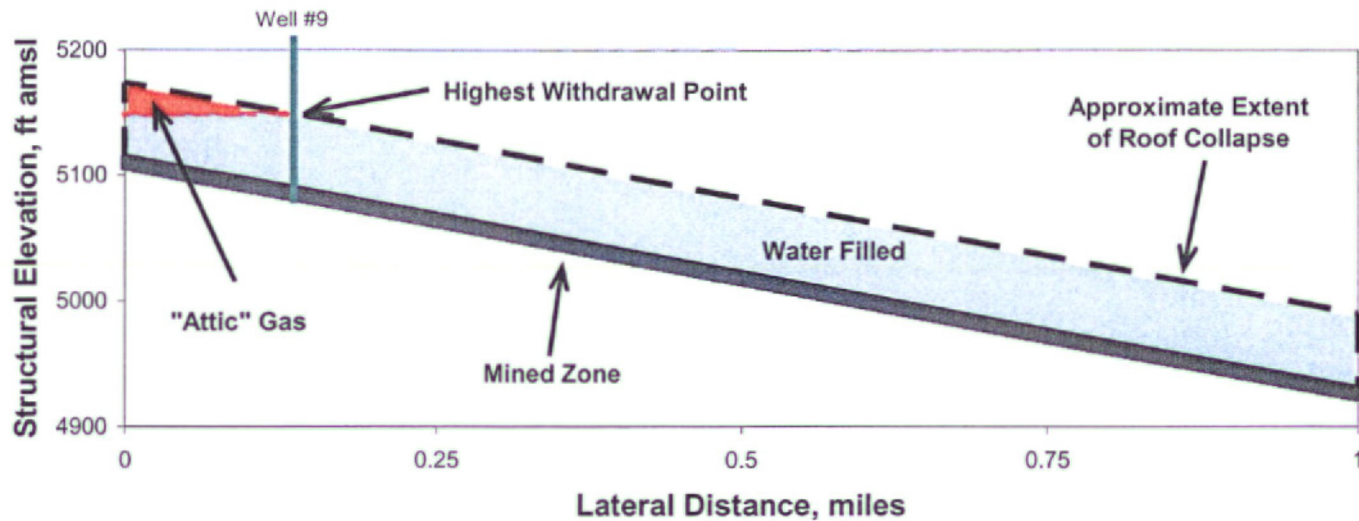


Figure 5: Current Conditions (2003)



**Figure 6: Conceptual Cross Section of Facility after Filling with Water**



**Figure 7: Leyden Decommissioning Material Balance**

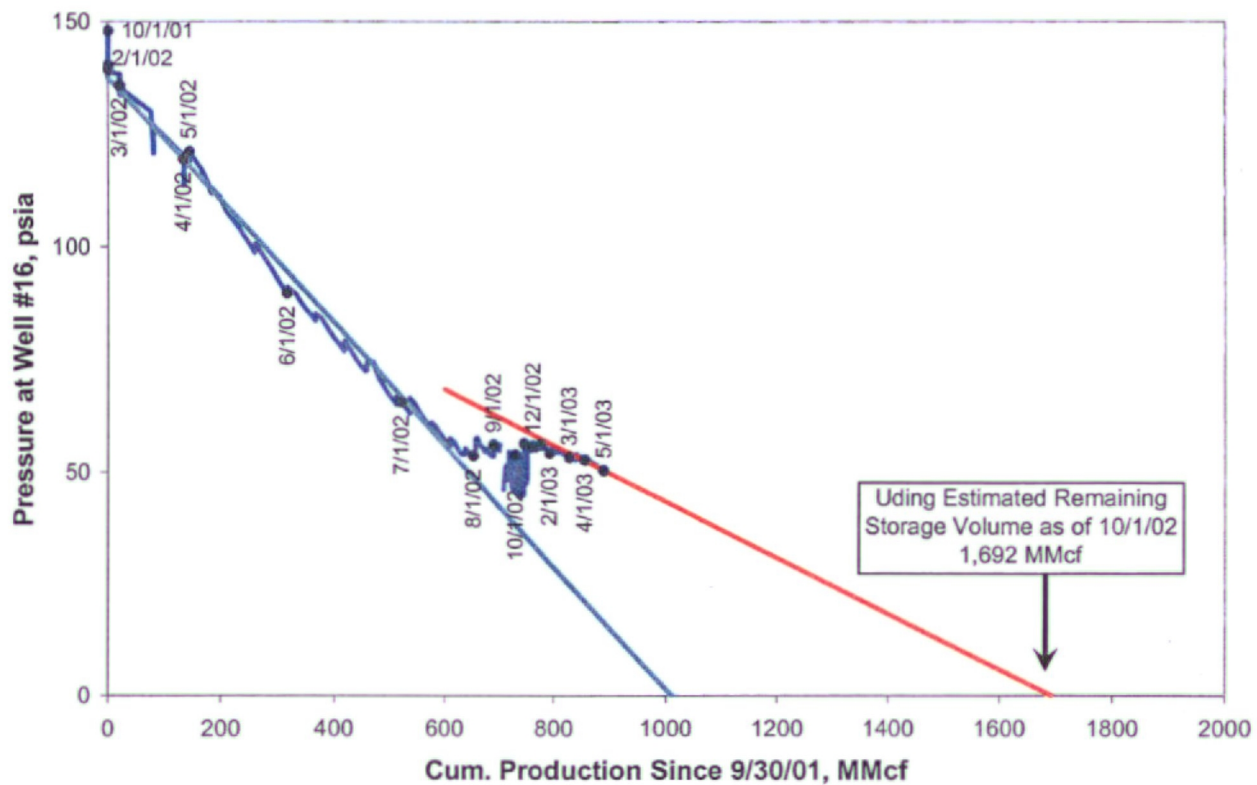


Figure 8: Vent Performance of Leyden Well #31

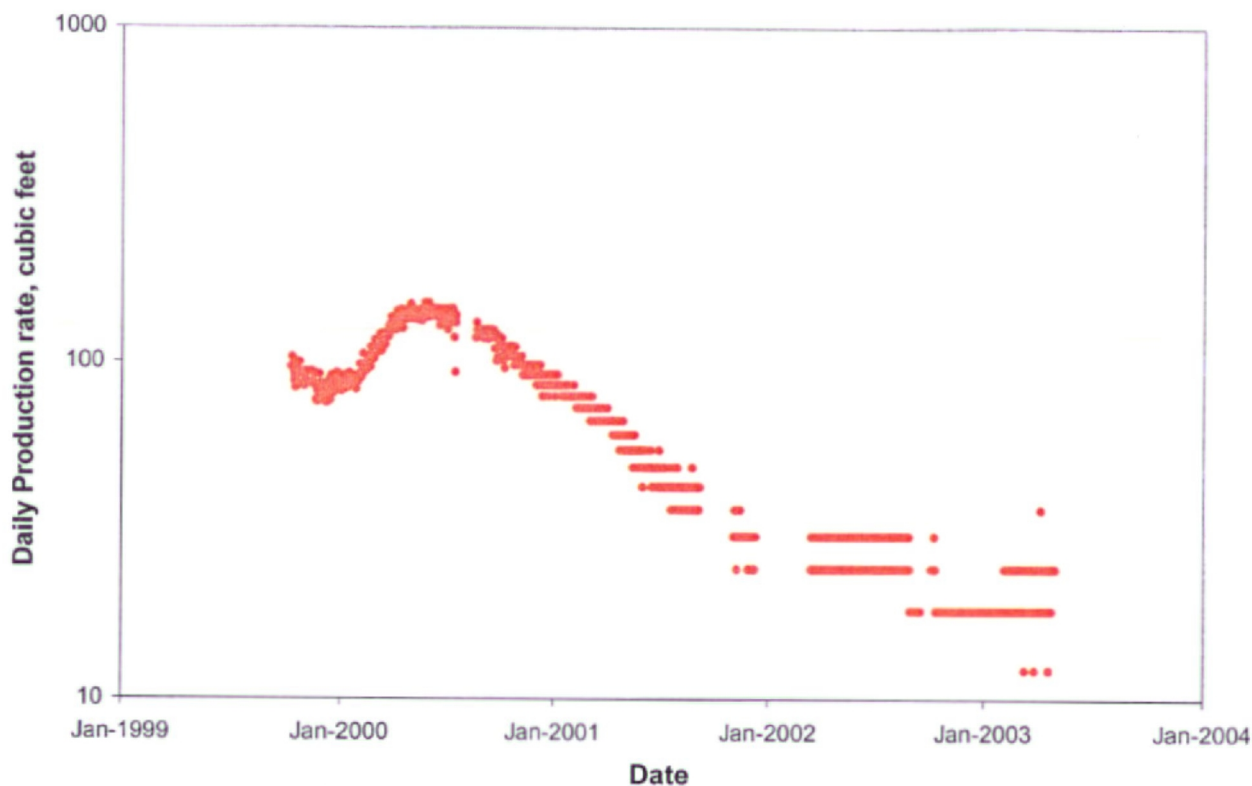


Figure 9: Pressures at Various Leyden Wells

